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Title: **FAIL SAFE DRIVE FOR CONTROL OF MULTIPLE SOLENOID COILS**

Inventors: Brent Chian, a resident of Plymouth, Minnesota, United States and a citizen of Canada.

Assignee: Honeywell International Inc.
101 Columbia Road
P.O. Box 2245
Morristown, NJ 07962-2245

Fail Safe Drive for Control of Multiple Solenoid Coils

FIELD

The present invention relates generally to a fail-safe circuit, and more particularly, relates to fail-safe circuitry for independently controlling multiple solenoid coils. The invention is particularly useful in controlling solenoid-controlled pneumatic valves in combustible fuel-fired apparatuses.

BACKGROUND

Water heaters, furnaces, boilers, fireplaces, and other combustible fuel-fired equipment or appliances generally include valving systems to connect and control the flow of gas between an external supply and their respective burners. These valving systems typically include normally closed, solenoid-controlled pneumatic valves so that the external supply of gas, which may be delivered to the valving systems via pipes connected to a gas supplier, a locally situated tank and/or other delivery system, only flows when called for. In other words, gas does not flow unfettered in normal operation.

Without such valving systems, not only would freely venting the gas supply be an extreme waste of a resource, but also, when vented in a closed or semi-closed environment, the gas volume in the locale of the gas-fired equipment might build. The build up of gas may create a potentially dangerous situation. For example, an explosion could result with a given amount of gas build-up and an ignition source. Over time, fairly sophisticated valving and valve-control systems have been developed to safely supply gas to the gas-fired equipment. Such systems, for example, may include direct-ignition combustion systems.

To limit inadvertent gas flow, some direct-ignition combustion systems employ a series of redundantly plumbed solenoid-controlled pneumatic valves. For gas to flow, all of the valves need to be open. Generally, to control the opening and closing of the solenoid valves, direct-ignition combustion systems typically employ electronic drive mechanisms, which have a

plurality of electronic components. In operation, these electronic drive mechanisms energize and de-energize the solenoid coil of the solenoid-controlled pneumatic valves, which in turn causes the mechanical portion of the valves to open and close. And when all valves are mechanically open, gas flows.

5   Unfortunately, however, the electronic drive mechanisms and the electronic components can fail. When one or more components of these mechanisms fail, valves can be left open and cause gas to flow, which can cause an unsafe condition. To prevent this from happening, fail-safe electronic drives are employed. These fail-safe drives can prevent inadvertent flow through the redundantly plumbed valves when critical components in the drive systems fail. When the

10   components of these systems fail, it would be desirable to determine which of the drive components have failed.

In typical fail-safe systems, two solenoid-controlled pneumatic valves are used. In these systems, the fail-safe mechanisms (i) control only one valve (and the other valve is controlled by another mechanism), (ii) employ separate mechanisms to control each of two valves, or (iii) use

15   energy transferred from control of one valve to control the second valve (i.e., the first valve must be on for the second valve to turn on). As such, the fail-safe systems either lack the ability to independently control each of the valves single handedly or require a plurality of fail-safe circuits to independently control each of the valves.

Thus, it would be desirable to have a single, low-cost, fail-safe mechanism (e.g., fail safe

20   circuitry) to (i) independently control each of the valves during normal operation, (ii) independently control each valve during testing, and (iii) diagnose and isolate faulty circuitry when one or more of the fail-safe mechanism and/or components thereof fails.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments are described below in conjunction with the appended drawing Figures, wherein like reference numerals refer to like elements in the various Figures, and wherein:

5   Fig. 1 is a first block diagram illustrating an exemplary combustible-fuel-delivery system having a valving system and a fail-safe drive system in accordance with an exemplary embodiment;

Fig. 2 is a second block diagram illustrating a second exemplary combustible-fuel-delivery system having a valving system and a fail-safe drive system in accordance with an 10   exemplary embodiment;

Fig. 3 is a first set of steady state curves illustrating various voltages and currents for operating the fail-safe drive system in accordance with an exemplary embodiment;

Fig. 4 is a second set of steady state curves illustrating various voltages and currents for operating the fail-safe drive system in accordance with an exemplary embodiment;

15   Fig. 5 is a third set of steady state curves illustrating various voltages and currents for operating a fail-safe drive system in accordance with an exemplary embodiment;

Fig. 6 is a fourth set of steady state curves illustrating various voltages and currents for operating a fail-safe drive system in accordance with an exemplary embodiment;

Fig. 7 is a third block diagram illustrating a third exemplary fail-safe drive system with 20   passive-current-limiting circuitry;

Fig. 8 is a fourth block diagram illustrating a fourth exemplary fail-safe drive system with passive-current-limiting circuitry and high-side drive circuitry;

Fig. 9A is a fifth block diagram illustrating a fifth exemplary fail-safe drive system with passive-current-limiting circuitry and low-side drive circuitry;

25   Fig. 9B is a sixth block diagram illustrating a sixth exemplary fail-safe drive system with passive-current-limiting circuitry and low-side drive circuitry;

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Fig. 10 is a seventh block diagram illustrating a seventh exemplary fail-safe drive system with active-current-regulation circuitry;

Fig. 11 is an eight block diagram illustrating a eighth exemplary fail-safe drive system for low input voltage applications; and

Fig. 12 is a ninth block diagram illustrating a ninth exemplary fail-safe drive system for low input voltage applications.

DETAILED DESCRIPTION OF PRESENTLY PREFERRED EMBODIMENTS

In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be understood that the present invention may be practiced without these specific details. In other instances, well-known

5   methods, procedures, components and circuits have not been described in detail, so as not to obscure the present invention. Further, the presently preferred embodiments disclosed are for exemplary purposes only and other embodiments may be employed in lieu of or in combination with the embodiments disclosed.

1.   Overview

10   Fig. 1 illustrates a combustible-fuel-delivery system 100 according to an exemplary embodiment. The combustible-fuel-delivery system 100 may include a valving system 102 and a fail-safe-drive system 140. The fail-safe-drive system 140 is capable of, but not limited to, (i) controlling the valving system 102 under normal operating conditions, (ii) performing fail-safe shutdown when the fail-safe-drive system 140 fails, and/or (iii) diagnosing failures of the

15   combustible-fuel-delivery system 100 when failures occur.

The valving system 102 may pneumatically couple an upstream supply 104 of combustible fuel to a downstream, combustible-fuel-fired apparatus 106. Included in the vavling system is a pipe or manifold 108 having an internal passageway 110 through which combustible fuel may flow.

20   The downstream flow of combustible fuel may pass through passageway 110 via a series arrangement of first and second solenoid-controlled valves 112, 122 (hereinafter referred to as "first and second valves"). The first and second valves 112, 122 have respective inlet ports 114, 124 for receiving the combustible fuel, and respective outlet ports 116, 126 for supplying the combustible fuel.

As shown, the first valve 112 is located upstream from the second valve 122. When both of the first and second valves 112, 122 are opened, the downstream flow of combustible fuel from the upstream supply 104 may pass to the combustible-fuel-fired apparatus 106. Given the redundancy and the corresponding safety of the serially-plumbed first and second valves 112, 122, if either is not open, then the combustible fuel will not flow to the combustible fuel-fired apparatus 106.

While only two valves are shown, namely, the first and second valves 112, 122, more than two of such valves may be pneumatically plumbed in series for additional redundancy, which in theory adds additional safety. In such case, all the redundant valves must be "open" to allow the flow of combustible fuel from upstream supply 104 to the combustible fuel-fired apparatus 106.

The fail-safe-drive system 140 controls the operation of the first and the second valves 112, 122 by facilitating the opening or "actuating" and closing or "de-actuating" the respective first and second valves 112, 122. Operating the fail-safe-drive system 140 at a given duty cycle or within a range of duty cycles allows for independent actuation and/or de-actuation of the valves 112, 122. For instance, the first valve 112 may be actuated when operating the fail-safe drive system 140 at a first duty cycle, the second valve 122 may be actuated when operating the fail-safe-drive system 140 at a second duty cycle, and both the first and second valves 112, 122 may be actuated at a third duty cycle.

The architecture of the fail-safe-drive system 140 may include a fail-safe circuit 142 that can be coupled to an input power supply 162. The fail-safe circuit 142 may be constructed from a switch 144, first and second solenoid coils 146, 156, and an energy-transfer device 150 that is coupled between the first and second solenoid coils 146, 156.

The first and second solenoid coils 146, 156 may control the operation of the first and second valves, respectively, between unactuated and actuated states. To initially actuate or in the parlance of solenoid-controlled valves, "pull-in," the first and/or second valve 112, 122, the

valve's respective load (i.e., first solenoid coil 146 and the second solenoid coil 156) must experience a threshold "pull-in current" to actuate from an unactuated state. This pull-in current is generally greater than the amount of current that is required for maintaining the valve in an actuated state. Thus, after a valve is initially actuated, a smaller maintenance or "holding

5   current" and its corresponding voltage are required to "hold-in" the valve in the actuated state.

For an unactuated or non-pulled-in valve, a current that is less than the pull-in current threshold can flow though the valve's load, but will not generate enough magnetic field to cause the valve to operate in an actuated state. Similarly, if, after operating in an actuated state, the current through the valve's load drops below the holding current threshold and thereby fails to

10   generate enough magnetic field, the valve will de-actuate and operate in an unactuated state even though some amount of current may be still flowing through the valve's load.

When closed, the switch 144 can cause a first current to flow in the first solenoid coil 146 by coupling an input voltage across it. The amount of first current flowing depends on the duration of the closure time of the switch 144. The longer the duration, the greater the amount of

15   current flows. With a long enough duration, the first current will build up to the point where the first solenoid coil 146 saturates.

When open, the switch 144 decouples the input voltage across the first solenoid coil 146. This allows any first current stored in the coil to decay or "freewheel." If the duration of the open time is short, the first current might not significantly decay. With a long enough duration,

20   the first current may decay to zero. The decay of the first current, however, may be affected by energy stored in the energy-transfer device 150, as will be described in more detail below. Adjusting the duration of the open and/or close time of the switch 144 can determine whether the average amount of the current over the duty cycle is sufficient to pull-in, hold-in and/or release the valve 112.

25   Accordingly, the switch 144 may be operated at various switching-cycle rates that ultimately determine the duty cycle of the fail-safe-drive system 140. That is, each switching

cycle defines successive "on" and "off" states. Each of the successive on and off states has a given duration. Shorter or longer durations of either the on or off states can change the proportion of conducting time of the switch 144 over a given cycle, which in turn define a duty cycle. By varying the switching cycle rates, the duty cycle can be correspondingly changed.

5   Thus, during the on state of any duty cycle, the switch 144 can cause the first current to flow by coupling the input voltage across the first solenoid coil 146. If the first current meets or exceeds the pull-in current threshold, then the first valve 112 will actuate. If the first valve 112 is already actuated and the first current meets or exceeds the hold-in current threshold, then the first valve 112 may be maintained in the actuated state.

10   When the first current falls below the hold-in current threshold, the first valve 112 will de-actuate. If, however, the first valve 112 is not already actuated and the first current fails to meet the pull-in current threshold, then the first valve will fail to actuate.

At certain duty cycles, a potential may be established in the energy-transfer device 150. This potential can change in polarity, and when used in combination with the input voltage, it

15 may cause a second current to flow in the second solenoid coil 156. If the second current meets or exceeds the pull-in current threshold, which may or may not be the same amount as for the first valve, the second valve 122 will actuate.

If the second valve 122 is already actuated, this combination may help maintain the second current above the hold-in current threshold. If not already actuated, the second valve 122

20 might not actuate when the second current fails to meet the pull-in current threshold. Similarly, when the second current fails to stay above the hold-in current threshold, the second valve 122 will de-actuate. The pull-in and hold-in current thresholds for the second solenoid coil 156 may or may not be the same as that for the first solenoid coil 146. For convenience, however, these thresholds will be generically referred to hereinafter the as "pull-in threshold" and "hold-in

25 threshold" for both the first and second solenoid coils 146, 156.

During the off state of any of the duty cycles, the potential established in the energy-transfer device 150 may affect the decay rate of the first and second currents flowing through their respective first and second solenoid coils 146, 156. Depending on the amount of energy and the polarity of the potential established in the energy-transfer device 150, the rate of decay of the first and/or second currents can be varied. The amount of energy and the potential established in the energy-transfer device 150 depends upon which duty cycle or range of duty cycles that the fail-safe-drive system 140 is operating at.

The following describes exemplary operation of the fail-safe-drive system 140 at (A) a high duty cycle, during which only the first valve 112 is actuated; (B) a low duty cycle, during which only the second valve 122 is actuated, and (C) a mid-range duty cycle, during which both the first and second valves 112, 122 are actuated. The fail-safe drive system 140 may be operated at other duty cycles, such as a very low duty cycle, during which neither of first and second valves 112, 122 are actuated. The high duty cycle may have an on-state duration of approximately 70 to 100 percent of a given switching cycle. The low duty cycle defines an on-state duration of approximately 10 to 30 percent of a given switching cycle. The mid-range duty cycle defines an on-state duration of approximately 50 percent of a given switching cycle.

A. High Duty Cycle

During the on-state of one or more switching cycles at the high duty cycle, the switch 144 couples the input voltage supplied from the input power supply 162 across the first solenoid coil 146 so as to cause the first current to meet or exceed the pull-in current threshold. This causes the first valve 112 to operate in the actuated state.

During the off state, a potential established in the energy-transfer 140 helps to maintain the first current above the hold-in threshold. When the first current is above the hold-in threshold, the first valve 112 can be sustained in the actuated state. Once actuated, subsequent on states cause the first valve 112 to stay actuated. Thus, after the initial pull-in, the average of the first current is maintained above at least the hold-in threshold.

In addition to having a magnitude of about the input voltage, the potential established in the energy-transfer device 150 has a positive polarity from between the first solenoid coil 146 to the second solenoid coil 156. After the switch decouples the input voltage, the first current freewheels from the first solenoid coil 146. But instead of decaying freely, its rate of decay is

5   slowed by the potential established in the energy-transfer device 150. As a consequence, the first current that freewheels from the first solenoid coil 146 causes at least a portion of the energy stored in the energy-transfer device 150 to deplete.

After the switch 144 re-couples the input voltage across the first solenoid coil, however, the input voltage replenishes the depleted portion of the energy stored in the energy-transfer

10   device. Because of the short duration of the off state at the high duty cycle, the switch 144 re-couples the input voltage before the first current can drop below the hold-in current, thereby causing the first current to be maintained over hold-in threshold.

Moreover, the potential established in the energy-transfer device 150 limits the second current flow so as to cause it to be below the pull-in threshold during both the on and off states.

15   Thus, during the on-state of the switch 144, the application of the input voltage causes energy-transfer device 150 to store energy and establish the potential having the polarity noted above. At this potential, the energy-transfer device 150 causes a little or no second current to flow, thereby causing the second valve 122 to operate in an unactuated state.

During the off state, the magnitude of the established potential drops as a result of the

20   first current depleting a portion of the energy stored in the energy-transfer device 150. Given the short duration of the off state, any second current resulting from this potential does not rise to the level of the pull-in current threshold. Consequently, the second valve 122 operates in the unactuated state.

B. Low Duty Cycle

25   When the switch 144 is operating in the on state at the low duty cycle, it couples the input voltage across the first solenoid coil 146 as before. But because the duration of the on state is

short, the first current fails to rise above the hold-in and pull-in thresholds, which causes the first valve 122 to operate in the unactuated state.

On the other hand, the combination of the input voltage and the potential established in the energy-transfer device 150, which has a positive polarity from between the second solenoid

5 coil to the first solenoid coil, causes the second current to exceed the pull-in threshold. This in turn causes the second valve 122 to operate in the actuated state.

During the off state, any residual current in the first solenoid coil 146 decays in magnitude, and thus, does not rise above the pull-in threshold. This in turn causes the first valve 112 to operate in the unactuated state. And because of the polarity of the potential established in

10 the energy-transfer device 150, the residual first current rapidly decays. As part of its decay, the first current freewheels from the first solenoid coil 146 boosting the potential established in the energy-transfer device 150. This boost may assist in causing the second current to exceed the pull-in threshold during the on state.

In addition to affecting the decay of the first current, the energy-transfer device 150 also

15 provides a freewheeling path for the second current. This freewheeling path may assist in limiting the decay rate of the second current so that the average of the second current can be maintained above the pull-in threshold and the second valve 122 in the actuated state. After the switch re-couples the input voltage across the first solenoid coil 146, the potential established in the energy-transfer device 156 helps to boost the level of the second current, and then the cycle

20 starts anew.

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C. Mid-range Duty Cycle

As noted, the mid-range duty cycle has an on or off state duration of approximately 50 percent of the given switching cycle. Over entire switching cycle, little or substantially no net potential is established in the energy-transfer device 150. When the switch 144 couples the input

5   voltage across the first solenoid coil 146 during the on state, it causes the first current to exceed the pull-in threshold, which in turn causes the first valve 112 to operate in the actuated state. During the same period, any transient potential established in the energy-transfer device 150 in combination with the input voltage causes the second current to exceed the pull-in current theshold. This causes the second valve 122 to operate in the actuated state.

10   During the off state, the energy-transfer device 150 provides freewheeling paths for the first and second currents. These freewheeling paths in combination with the lack of any substantial potential established in energy-transfer device 150 assist controlling the rate of decay of the freewheeling currents so as to maintain the first and second currents above their respective hold-in currents. As such, the first and second valves 112, 122 are maintained in the actuated

15   state.

2.   Exemplary Architecture

Fig. 2 illustrates the combustible-fuel-delivery system 200 according to another exemplary embodiment. The combustible-fuel-delivery system 200 is similar to the combustible-fuel-delivery system 100 illustrated in Fig. 1, except as described herein. With

20   reference to Fig. 2, high-side and low-side supply conductors 164, 166 collectively couple the input power supply 162 to the fail-safe circuit 142. In this exemplary embodiment, the energy-transfer device 150 may be embodied as a capacitor 152 and rectifier 154.

The input power supply 162 is operable to source an input electrical signal having a positive voltage V_{in} and a corresponding input current from between the high-side supply

25   conductors 164 and the low-side supply conductor 166. For example, the input power supply 162 can be configured to supply enough current at a nominal voltage of 5 volts DC so as to

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maintain the high-side supply conductor 164 at a system reference potential or nominal voltage and the low-side supply conductor 166 at a low-side reference potential and/or earth ground. The voltage V_{in}, however, may be significantly greater, e.g., 20 times greater, than a valve's specified pull-in voltage. The fail-safe circuit 142 may use the input electrical signal for
5   controlling the actuation of the first and second solenoid-controlled valves 112, 122.

The input power supply 162 may be deployed as a transformer and rectifier bridge combination, and/or other voltage rectification and regulation components as known in power source regulation. Alternatively, instead of being sourced by traditional power source regulation components, an input electrical signal may be supplied by a thermopile, and/or other analog or
10   digital source (not shown). The input power supply 162 may also include various additional switches and circuits for achieving desired safety, timing, and sequencing functions.

When closed, the switch 144 couples the input electrical signal so as to cause sourced current to flow into a first common node 172. Depending on the duty cycle, the sourced current can flow into the first solenoid coil 146 and/or the capacitor 152.

15   The switch 144 may be constructed from mechanical or electromagnetic-relay-controlled elements, solid-state or semiconductor-based elements, and/or any other switching elements that allow for a variable duty ratio. Accordingly, the construction of the switch 144 may be discrete, monolithic and/or hybrid. Thus, the architecture of the switch 144 may include one or more metal oxide semiconductor field effect transistors (MOSFETs), one or more junction field effect
20   transistors (JFETs), one or more bipolar-junction transistors (BJTs), and/or any other monolithic, discrete or hybrid switches capable of switching at various frequencies and pass enough current.

Control signals, which can be illustratively represented by "S_1," control the duty cycle of the switch 144 (i.e., the fraction of time the switch is in a conducting state over a given switching cycle). These control signals S_1 are supplied by a control circuit (not shown), and may be
25   implemented using a microprocessor. Alternatively, other signal generators, such as pulse-width-modulation signal generators, pulse-frequency-modulation signal generators, and/or

feedback-controlled or hysteretic signal generators, may source the control signals S1. The control signals S_1 may be pulse-width modulated control signals, pulse-frequency-modulated control signals, hysteretic control signals, and/or other signals that may vary in magnitude, shape and frequency.

5   In the embodiment shown on Fig. 2, the first solenoid coil 146 is illustrated as its equivalent impedance, which may be modeled as a first inductor 148 and a first resistor 149. This equivalent impedance model is presented with simplicity so as not to obscure the details of the present embodiment. The actual impedance may be modeled differently and include other higher order components, such as back-emf inductors.

10   One end of the first solenoid coil 146 may be coupled to the switch 144 at the first common node 172. Its other end may be coupled to a common low-side or ground node 174, which, in turn, is coupled to the low-side conductor 166. This common low-side reference or ground node 174 may be earth ground or other low-side circuit reference potential and may be designed such that the common low-side reference or ground node 174 limits undesirable ground

15   loop currents. For convenience, however, the common low-side reference or ground node 174 will be collectively referred to as "common low-side- node" 174.

The rectifier 154 couples to the capacitor 152 at a second common node 176 and to the common-low-side node 174 in a reverse bias orientation. This orientation allows forward bias current to flow from the common-low-side node 174 to the second common node 176.

20   The second solenoid coil 156 is coupled in parallel with the rectifier 154. Similar to the first solenoid coil 146, the second-solenoid coil 156 is illustrated as its equivalent impedance, which includes a second inductor 158 and a second resistor 159. Like the first solenoid coil 146, this equivalent impedance model is presented with simplicity so as not to obscure the details of the present embodiment.

25   The capacitor 152 may be a non-polarized type having a voltage rating that is at least as high as the value of input voltage V_{in}, and in some embodiments, approximately two times the

value of V_{in}. In characterizing the capacitor 152, its energy storing capacity may be configured to provide a pull-in current for the second solenoid coil 156 at various given operating frequencies of switch 144.

The architecture of rectifier 154 may include (i) one or more diodes, such as Schottky

5   diodes; (ii) one or more synchronous rectifiers, which may be constructed from one or more enhancement or depletion mode NMOS or PMOS transistors; and/or (iii) any other discrete, monolithic, and/or hybrid rectifier having the ability to switch from a conducting state to a non-conducting state.

The following table contains exemplary values for properties of each of the components

10   of the fail-safe circuit 142.

Component	Properties
Switch 144	$R_{DS}-ON \le 0,2$
Capacitor 152	$3\mu F$, 50V
Rectifier 154	IN5817
First Solenoid Coil 146	250 mH
Second Solenoid Coil 156	250 mH
Resistor 149	12 Ω
Resistor 159	12 Ω

TABLE 1

3.   Exemplary Operation

The following is a general description of the operation of the combustible-fuel-delivery

15   system 200. The combustible-fuel-delivery system 200 may be operated in at least three modes. The first of these modes is a "VALVE SELECT" mode in which the fail-safe-drive system 140 drives one or the other of the first and second valves 112, 122 to an actuated state, but prevents

the combustible fuel from flowing from the upstream supply 104 to the combustible-fuel-fired apparatus 106.

The second mode is an "OFF" mode in which the fail-safe-drive system 140 does not drive either of the first and second valves 112, 122 to an actuated state, and thereby prevents the

5 combustible fuel from flowing from the upstream supply 104 to the combustible-fuel-fired apparatus 106. The third mode is an "OPERATIONAL" mode in which the fail-safe-drive system 140 drives both of the first and second valves 112, 122 to an actuated state, which allows the combustible fuel to flow from the upstream supply 104 to the combustible-fuel-fired apparatus 106.

10 Each of the Figs. 3-6 illustrate a set of steady state curves that represent various voltages and currents of elements of the fail-safe circuit 142 for each of the above listed modes. These curves are shown in reference to the control signal S_1 that operates the switch 144 at various duty cycles. The polarities of these curves are illustrated for exemplary purposes only, and not intended to provide for inflexible circuit analysis. And given the numerous variations and

15 possible combinations of solenoid coils, input electrical signals, and other components of fail-safe circuit 142, the actual value of the magnitudes of the curves are not shown.

A. VALVE SELECT MODE

In the VALVE SELECT mode, one or the other of the valves are held in actuated state by the fail-safe drive system 140. This can occur when one or the other of the first or second

20 solenoid coils 146, 156 experience a current sufficient to meet the pull-in threshold and thereafter experience a current sufficient to satisfy the hold-in threshold.

(1) Independent Operation of the First Valve

Fig. 3 is a first set of steady state curves 302-308 illustrating various currents and voltages of the fail-safe circuitry 142 operating at a high duty cycle, e.g., a duty cycle of about 80

25 to 100 %. At this duty cycle the fail-safe circuitry 142 may actuate the first valve 112 in accordance with the VALVE SELECT mode.

Referring now to Fig. 3, a first S1 curve 302, a first I_1 curve 304, a first V_{C1} curve 306, and a first I_2 curve 308 are shown according to the respective reference polarities illustrated in Fig. 2. The first S1 curve 302 represents the state, i.e., the on state or off state, of the switch 144. The first I_1 curve 304 represents the current I_1 flowing through first solenoid coil 146. Shown in

5   conjunction with current I_1 is an average over time of the current I_1 ("$\overline{I_1}$"). The first V_{C1} curve 306 represents the voltage across capacitor 152 "V_{C1}." The first I_2 curve 308 represents the current I_2 through the second solenoid coil 156. Like the first I_1 curve 304, current I_2 is shown in conjunction with an average over time of the current I_2 ("$\overline{I_2}$").

The steady state conditions of the curves shown in Fig. 3 occur after a brief transitory

10   period of one or more switching cycles of the switch 144 to the high duty cycle. The steady-state operation of the fail-safe circuit 142 may occur by way of the following example. At time t_1, control signal S_1 causes the switch 144 to transition to an off state from an on state. The switch 144 remains in the on state until time t_2.

The current I_1 begins to increase through first solenoid coil 146 after the switch 144

15   transitions to V_{in} at time t_1. Then after a short period, the current I_1 increases to a value that is approximately V_{in} divided by the value of the first resistor 149. Given that V_{in} and its corresponding input current are sufficient to source a pull-in current, the current I_1 flowing through the first solenoid coil 146 between time t_1-t_2 is sufficient to cause the first valve 112 to actuate.

20   In addition, the capacitor 152 charges through solenoid coil 156 to approximately -V_{in} and remains at -V_{in} until time t_2. Thus, only a small amount of current I_2 flows through the rectifier 154 and the second solenoid coil 156 since the second common node 176 and the common-low-side node 174 are at approximately the same potential. When the voltage on capacitor 152 reaches approximately -V_{in}, current I_2 decays to zero or a very low level. In

25   practice, the current I_2 is less than the pull-in threshold and may be less than the hold-in threshold.

At time t_2, the switch 144 transitions from the on state to the off state and remains in the off state until time t_3. The input power supply 162 therefore no longer supplies V_{in} between the first common node 172 and the common-low-side node 174. The voltage at the first common node 172 transitions from V_{in} to a voltage equivalent to the voltage across the capacitor 152 V_{c1}

5   less a voltage across the rectifier 154 "V_d." Being almost charged to V_{in}, however, the capacitor 152 may help maintain the current I_1 above at least the hold-in threshold while it freewheels through rectifier 154 and capacitor 152. The freewheeling current I_1, in turn, reduces any potential established in capacitor 152. Accordingly, the current I_2 developed from the change in potential established in the capacitor 152 difference flows through the second solenoid coil 156

10   as shown in first I_2 curve 308.

Before the freewheeling current I_1 can decay any significant amount and appreciably affect the potential established the capacitor 152, the control signal S_1 causes the switch 144 to begin a new switch cycle. During such time, the capacitor 152 again charges toward V_{in} and the current I_1 again becomes approximately V_{in} divided by the value of the first resistor 149. The

15   current I_2 reverses direction (i.e., flowing in the opposite direction of current I_2 flowing during the time t_1-t_2) and again decays to zero or a very low value.

Thus, the operation of the fail-safe circuit 142 at the high duty cycle allows the average current $\overline{I_1}$ flowing through first solenoid coil 146 over a switch cycle, such as the switch cycle from time t_1 to t_3, to rise above the pull-in threshold and remain at or above the pull-in and/or the

20   hold-in thresholds. Consequently, the first valve 112 may transition to and remain in the actuated state.

Conversely, the second valve 122 remains in the unactuated state since the average current $\overline{I_2}$ does not meet or exceed the pull-in and/or hold-in thresholds. In the unactuated state, the second valve 122 is not open. Unless the first outlet port 116 is vented or the second valve

25   122 is inadvertently open, opening only the first valve 112 does not provide a path for the combustible fuel to flow.

(2) Independent Operation of the Second Valve

Fig. 4 is a second set of steady state curves 402-408 illustrating various currents and voltages of the fail-safe circuitry 142 operating at a low duty cycle, e.g., a duty cycle of about 10 to 30%. At this duty cycle the fail-safe circuitry 142 may actuate the second valve 122 in

5   accordance with the VALVE SELECT mode.

In Fig. 4, a second S1 curve 402, a second I_1 curve 404, a second V_{C1} curve 406, and a second I_2 curve 408 are shown according to the respective reference polarities illustrated in Fig. 2. The second S1 curve 402 represents the on state and off state of the switch 144. The second I_1 curve 404 represents the current I_1 flowing through first solenoid coil 146. Shown in conjunction

10   with current I_1 is the average current $\overline{I_1}$. The second V_{C1} curve 406 represents the voltage across capacitor 152 "V_{C1}." The second I_2 curve 408 represents the current I_2 through the second solenoid coil 156. Like the first I_1 curve 404, current I_2 is shown in conjunction with the average current $\overline{I_2}$.

The steady state condition of the curves illustrated in Fig. 4 occur after a brief transitory

15   period of one or more switching cycles at the low duty cycle. At time t_1, the switch 144 transitions from an off state to an on state. The voltage between the first common node 172 and the common-low-side node 174 transitions from about 0 volts to about V_{in} and remain at V_{in} until time t_2.

After the transition at time t_1, the current I_1 increases in first solenoid coil 148, as shown

20   in the second I_1 curve 404. In addition, V_{in} is put in series with the potential established in the capacitor 152. This results in a potential higher than V_{in} being dropped across the second solenoid coil 156. Consequently, the current I_2 passing through the second solenoid coil 156 rises above the pull-in threshold. But given the short duration of the on state of the switch 144, the current I_1 does not rise above the pull-in threshold.

25   At time t_2, the switch 144 transitions from the on state to an off state. The current I_1 freewheels through rectifier 154 as the voltage at the first common node 172 attempts to

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approach minus infinity volts. This boosts the charge on the capacitor 152 V_{C1} as shown in curve 406. The freewheeling current I_1, however, will decay rapidly as compared with the current I_2 passing through the second solenoid coil 156 given the negative polarity of the charge on the capacitor 152 at the first common node 172. And because the switch 144 is open for a

5   long duration, the freewheeling current I_1 may decay to zero before the control signal S_1 causes the switch 144 to begin a new switch cycle, as shown by the second I_1 curve 402.

Consequently, at the low duty cycle, the average current $\overline{I_2}$ through the second solenoid coil 156 remains above the pull-in threshold, and average current $\overline{I_1}$ is kept below the hold-in-threshold. This, in turn, causes the second valve 122 to operate in the actuated state, while the

10   first valve 112 remains in the unactuated state.

B. OFF MODE

Fig. 5 is a third set of steady state curves 502-508 illustrating various currents and voltages of the fail-safe circuitry 142 operating at a very low duty cycle, e.g., a duty cycle of about 0 to 5%. At this duty cycle the fail-safe circuitry 142 does not drive either of the first and

15   second valves 112, 122 to an actuated state in accordance with the OFF mode.

The curves shown in Fig. 5 include a third S1 curve 502, a third I_1 curve 504, a third V_{C1} curve 506, and a third I_2 curve 508. Each of these curves is shown according to its respective reference polarities illustrated in Fig. 1. The third S1 curve 502 represents the on state and off state of the switch 144. The third I_1 curve 504 represents the current I_1 flowing through first

20   solenoid coil 146. The third V_{C1} curve 506 represents the voltage across capacitor 152 V_{C1}. In addition, the third I_2 curve 508 represents the current through the second solenoid coil 156. Shown in conjunction with the current I_1 and current I_2 are the average currents $\overline{I_1}$, $\overline{I_2}$, respectively.

When the switch 144 opens for extended periods of time, the currents I_1, I_2 and voltage

25   across the capacitor 152 V_{C1} rise to only a very low level. At this very low level, the currents I_1,

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I_2 stay below the hold-in and pull-in thresholds. Thus, the first and second valves 112, 122 do not actuate.

C. OPERATIONAL MODE

Fig. 6 is a fourth set of steady state curves 602-608 illustrating various currents and

5 voltages of the fail-safe circuitry 142 operating at a midrange duty cycle, e.g., a duty cycle from about 40 to 60%. At this duty cycle the fail-safe circuitry 142 may actuate both the first and second valves 112, 122 in accordance with the OPERATIONAL mode.

Referring Fig. 6, a fourth S1 curve 602, a fourth I_1 curve 604, a fourth V_{C1} curve 606, and a fourth I_2 curve 608 are shown according to the respective reference polarities illustrated in Fig.

10 2. The second S1 curve 602 represents the on state and off state of the switch 144. The second I_1 curve 604 represents the current I_1 flowing through first solenoid coil 146. Shown in conjunction with current I_1 is the average current $\overline{I_1}$. The second V_{C1} curve 606 represents the voltage across capacitor 152 V_{C1}. The second I_2 curve 608 represents the current I_2 through the second solenoid coil 156. Like the first I_1 curve 604, current I_2 is shown in conjunction with the average current

15 $\overline{I_2}$.

Like each of the other state diagrams, the fourth set of the steady state curves of Fig. 6 assume a steady state condition, which occurs after a brief transitory period of one or more switching cycles. At time t_1, the switch 144 transitions from an off state to an on state and remains in the on state until time t_2. This, in turn, causes the voltage at the first common node

20 172 to transition to and remain at V_{in} until time t_2.

The current I_1 rises above the pull-in threshold in response to V_{in} being applied across the first solenoid coil 146. And the current I_2 rises above the pull-in threshold in response to the input voltage V_{in} and the voltage across the capacitor 152 V_{c1} being applied across second solenoid coil 156. At the same time, the voltage V_{c1} may change from a low positive voltage to a

low negative voltage. This, however, may not substantially affect the first and second currents I_1 or I_2.

At time t_2, the switch 144 transition from the on state to the off state, and thereafter

5   remains in the off state until the next switch cycle at time t_3. Given that current cannot change instantaneously in inductors, the current I_1 freewheels through rectifier 154 and the capacitor 152, and then returns to the first the solenoid coil 146. As this happens, the freewheeling current I_1 flowing through the rectifier 154 may slightly charge the capacitor 152, as shown in the fourth V_{C1} curve 306. Also, the current I_2 freewheels through rectifier 154. Consequently, both the first and second average currents $\overline{I_1}$, $\overline{I_2}$ stay above the pull-in and hold-in thresholds. Thus, both the

10   first and second valves 112, 122 are in an actuated state. As such, the first and second valves 112, 122 are open, which in turn, allows combustible fuel to flow to the piece of combustible-fuel-fired equipment 106.

D. PASSIVE CURRENT LIMITING CIRCUIT

Using supplemental circuitry, additional fail-safe protection may be provided to enhance

15   the level of fail-safe protection already provided by the architecture, arrangement and operation of the fail-safe circuit 142. Referring to Fig. 7, a third embodiment of the fail-safe-drive system 140 is illustrated. The fail-safe-drive system 140 may be deployed as the fail-safe circuit 142 as shown in Fig. 2 in combination with a passive-current-limiting circuit 732.

The passive-current-limiting circuit 732 and may include a parallel combination of a first-

20   current-limiting resistor 736 and a second capacitor 734 in series with a second-current-limiting resistor 738. This combination may be coupled between the switch 144 and the first-common node 172. In particular, the first-current-limiting resistor 736 has its first end coupled to the switch 144 and its second end coupled to a third-common node 740. The second-current-limiting resistor 738 has its first end coupled to the third common node 740, and its second end

25   coupled to the first-common node 172. The second capacitor 734 has its first end coupled to the switch 144 and its second end coupled to the third-common node 740.

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The second capacitor 734 may be a polarized type, as opposed to the type of the first capacitor 152. Polarized capacitors, as know in the art, are significantly less expensive than their non-polarized counterparts are. Thus, it would be desirable to use the less expensive polarized capacitor to save costs, when possible. The second capacitor 734, however, may be a non-

5   polarized type.

As noted above, the input power supply 162 may source an input electrical signal that is able to provide a current to the first solenoid coil 146 that is much greater than the pull-in current. Sourcing such a current may be necessary to supply a current greater than the pull-in threshold for the second solenoid coil 156, especially during low or midrange duty cycles. In

10   such case, however, the current I_1 flowing though the first solenoid coil 146 may be wasting energy through joule loss. This may reduce the life the solenoid coil 146 of the first valve 112 and resultant operation and reliability of the fail-safe circuit 142.

By employing the passive-current-limiting circuit 732, the current sourced from the input power supply 162 passes through the first and second current-limiting resistors 736, 738 limiting

15   the amount of current I_1 flowing through the first solenoid coil 146. Being in parallel with the first current-limiting resistor 736, the second capacitor 734 may reduce the total impedance of the current limiting circuit 732 at lower duty cycles when less current limiting may be desired, and have a lesser effect as the duty cycle increases when more current limiting may be desired. The passive-current-limiting circuit 732 may allow a progressively smaller voltage to be dropped

20   across first solenoid coil 146 as duty cycle increases, so that the current I_1 can sufficiently rise above the pull-in threshold. The current I_1, however, might not significantly exceed the pull-in threshold. The amount of voltage drop reduced by the passive current-limiting network at high and low duty cycles can be adjusted by the voltage-divider ratio of the first and second current-limiting resistors 736, 738.

25   The values for the first and second current-limiting resistors 736, 738 and capacitor 732 may be chosen to match the first and second solenoid coils 145, 156 and energy-transfer device

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150 so that at any duty cycle, the first and second currents I_1, I_2 may be at a safe level. This safe level may be, for example, at 1.5 times of the pull-in current level. An exemplary set of component values is provided in the Table. 2 below.

Component	Value
Vin	10 volt
Resistor 736	200 ohms
Resistor 738	160 ohms
Capacitors 734, 152	3.3 uF
Solenoid coils 148, 158	250 mH
Resistors 149, 159	12 ohms
Rectifier 154	1N5817
Switch 144	Rds_on < 0.2 ohm
Pull-in current	25 mA
Hold current	5 mA

TABLE 2

5   Additionally, the fail-safe circuit 142 may limit the first and second currents I_1, I_2 so that the first and second valves 112, 122 are not pulled-in simultaneously at any duty cycle. For instance, control signals S1 may be issued in a certain sequence so that only one of the first and second valves 112, 122 can be pulled-in at any time. In one exemplary sequence, the fail-safe circuit 142 may be first operated a duty cycle from about 95% to pull-in only the first valve 112.

10   Next, the duty cycle may be reduced to about 25% to pull-in the second valve 122, while holding the first valve 122 above the hold-in threshold. Lastly, the duty cycle may then be increased to about 50% to keep both the first and second valves 112, 122 actuated.

At the 50% duty cycle, the first and second currents I_1, I_2 are below the pull-in threshold, but are maintained above the hold-in thresholds. Using the exemplary values in Table 2, the first

15   and second currents I_1, I_2 at the 50% duty cycle may be at about 18 mA, which is below the pull-

in thresholds, yet above the hold-in thresholds. Thus, the first and second valves 112, 122 will not be pulled in at the 50% duty cycle without first experiencing the other duty cycles.

E. FAIL-SAFE PROTECTION

In fail-safe systems generally, unsafe conditions have to be prevented when any

5 component of such system fails. In the present context, when a failure condition occurs, the fail-safe circuit 142 may be shut down or otherwise prevented from unsafe operation. The fail-safe circuit 142 may be shut down immediately or, alternatively, after the completion of the current operation cycle. The fail-safe drive system 140 can be consider fail-safe, if, for example, the operation of the system is inhibited after a failure of one or more components of the fail-safe

10 drive system 140 is detected.

In an exemplary direct-ignition-valve-control system, the fail-safe circuit 142 may be used in conjunction with direct ignition and flame sensing technologies to test for proper operation of the system. The proper operation of the systems may be detected by independently actuating each of the first and second valves 112, 122, and then checking the gas flow to the fuel-

15 fired apparatus. Using such a scheme, the system may be shut down if either of the first and second valves 112, 122 fails to actuate, when requested, or if the fail-safe circuitry fails to open either of the first or second valves 112, 122.

These conditions may be detected using the following sequence of operating the fail-safe circuitry 142. First, operate the fail-safe circuitry 142 at, for example, a 0 duty cycle so that both

20 the first and second valves 112, 122 are closed. Next, change the fail-safe circuitry 142 to a duty cycle of about 95% so as to actuate only the first valve 112. After actuating the first valve 112, attempt to ignite the combustible fuel and attempt to sense for the presence of a flame. If a flame is sensed, then the second valve 122 or the fail-safe circuit 112 has failed. In such case, the operation of the fuel-fired apparatus 106 may be inhibited, halted or otherwise stopped. The fail-

25 safe-drive system 140 may then provide a fault indicator, e.g.., an illuminating light-emitting diode, to alter that the fuel-fired apparatus 106 may need to be serviced.

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If flame is not sensed, then change the duty cycle of the fail-safe circuitry 142 to 0% to de-actuate the first valve 112 and then change to a low duty between about 20 to 30% to actuate the second valve 122 . Again, attempt to ignite the combustible fuel and sense a flame. If a flame is sensed, then the first valve 112 or the fail-safe circuit 142 has failed. On the other hand,

5   if a flame is not sensed, then the fail-safe-drive system 140 may proceed to the normal operation.

Further, when any of the components of the safe circuit 142 fails, combustible fuel should not flow from the upstream supply 104 to the combustible fuel-fired apparatus 106. As noted above, the switch 144 is controlled by the control signal S_1. If, for example, the switch 144 or signal generator that issues the control signal S_1 fails, then the switch 144 may stay in the on-

10   state. This, in turn, may cause a constant application of V_{in} across the first solenoid coil 146. Responsively, the fail-safe circuit 142 may transition to VALVE SELECT MODE and operate only the first valve 112 instead of operating both the first and second valves 112, 122. If the switch 144 fails as an open circuit as a result of the signal generator or the switch 144 itself, then the fail-safe circuit 142 may transition to the OFF MODE.

15   Moreover, an examination of failure modes for each of the components of the fail-safe circuit 142 will show that when a component of the fail-safe circuit 142 fails, no more than one of the first and second valves 112, 122 will operate in an actuated mode. TABLE 3 lists possible single-component failure modes for the fail-safe circuitry 142 with the passive current limit circuitry 732.

20

First failed Component	At least one valve is closed or can be controlled?	Description
First solenoid coil 146 shorted	Yes, both valves closed	
First solenoid coil 146 open	Yes, both valves closed	
second solenoid coil 156 shorted	Yes, second valve closed	
Second solenoid coil 156 open	Yes, second valve closed	
Rectifier 154 open	Yes, second valve closed	Average second current is zero

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Rectifier 154 shorted	Yes, second valve closed	Average second current is zero
Capacitor 152 open	Yes, second valve closed	second current is zero
Capacitor 152 shorted	Yes, both valves can be closed by 144	
Switch 144 open	Yes, both valves closed	
Switch 144 shorted	Yes, second valve closed	
Resistor 736 open	Yes, both valves closed	
Resistor 736 shorted	Yes, both valves can be closed by 144	First and second currents are higher
Resistor 738 open	Yes, both valves closed	
Resistor 738 shorted	Yes, both valves can be closed by 144	First and second currents are higher
Capacitor 734 open	Can not pick valve 156	
Capacitor 734 shorted	Yes, both valves can be closed by 144	First and second currents are higher

TABLE 3

In an alternative embodiment, an optional second electronic switch (not shown) may be inserted between nodes 172 and 174 to increase safety when two components fail. This second switch may be used to short the first solenoid coil 146 when both the switch 144 and capacitor 152 fail shorted. Consequently, both of the first and second valves 112, 122 can not be actuated simultaneously. But if already actuated, the second switch allows the fail-safe circuitry to shut down the first and second valves 112, 122 by shorting the node 172 to 174.

(1) High Side Drive Circuit

Fig. 8 illustrates a fourth embodiment of the fail-safe-drive system 140 in which another level of fail-safe protection may be provided. In this exemplary embodiment, the fail-safe-drive system 140 may be deployed with the fail-safe circuit 142 as shown in Fig. 2 in combination with the passive-current-limiting circuit 732 and a high-side-drive circuit 850. The high-side-drive circuit 850 is particularly useful when both of the first and second solenoid coils 146, 156 have a common ground.

The high-side-drive circuit 850 includes the switch 144 in the form of a P-channel enhancement type MOSFET ("P-channel MOSFET") and an AC coupling network 852. The P-channel MOSFET 144 may have its drain coupled to the passive-current-limiting circuit 732, its source coupled to the high-side supply conductor 164, and its gate coupled to the AC coupling network 852.

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The AC coupling network 852 may include an AC coupling rectifier 854, an AC coupling resistor 856, and an AC coupling capacitor 858. The AC coupling rectifier 854 may be coupled between the gate and source of the P-channel MOSFET such that the AC coupling rectifier 854 will allow a forward bias current to flow from the gate to the source. The AC coupling resistor

5   856 may be coupled between the gate and source of the P-channel MOSFET. The AC coupling capacitor 858 may have a first end coupled to the gate of the P-channel MOSFET and a second end for receiving the control signal S_1 from the signal generator.

The AC coupling network 852 ensures that the P-channel MOSFET 144 can only be turned on when the control signal S_1 has an alternating signature. Thus, if the signal generator

10   (e.g., microprocessor) issuing the control signal S_1 fails to provide an alternating signature, the switch 144 will remain in its off state. Further, the AC coupling network 852 ensures that the P-channel MOSFET 144 needs a negative voltage between its gate relative to its source to turn on.

(2) Low Side Drive Circuit

Figs. 9a and 9b illustrate fifth and sixth embodiments of the fail-safe-drive system 140 in

15   which an alternative level of fail-safe protection may be provided. In the fifth embodiment, the fail-safe-drive system 140 includes the fail-safe circuit 142 as shown in Fig. 2 in combination with the passive-current-limiting circuit 732 and a low-side-drive circuit 950.

In the sixth embodiment, instead of the capacitor 152 being coupled between the first common node 172 and the rectifier 154 as shown in Fig. 2, the capacitor 152 may be coupled

20   between the common low-side- node 174 and the rectifier 154 as shown in Fig. 9. Also, the passive-current-limiting circuit 732 may be inserted between the common low-side- node 174 and the low-side-drive circuit 950 as shown. Other configurations for the low-side-drive circuit 950 are possible as well.

The low-side-drive circuit 950 is particularly useful when the first and second solenoid

25   coils 146, 156 do not have a common ground connection. The low-side-drive circuit 950 may include the switch 144 in the form of an N-channel enhancement type MOSFET (N-channel

MOSFET) and an AC coupling network 952. The N-channel MOSFET 144 may have its drain coupled to the common low-side- node 174, its source coupled to the low-side supply conductor 166, and its gate coupled to the signal generator through the AC coupling network 952.

The AC coupling network 952 may include an AC coupling rectifier 954, an AC coupling
5 resistor 956, and an AC coupling capacitor 958. The AC coupling rectifier 954 may be coupled between the gate and source of the N-channel MOSFET such that the AC coupling rectifier 954 will allow a forward-bias current to flow from the source to the gate. The AC coupling resistor 956 may be coupled between the gate and source of the N-channel MOSFET. The AC coupling capacitor 958 has a first end coupled to the gate of the N-channel MOSFET and a second end for
10 receiving the control signal S_1 from the signal generator.

The AC coupling network 952 ensures that the N-channel MOSFET 144 can only be turned on when the control signal S_1 has an alternating signature. Thus, if the signal generator (e.g., microprocessor) issuing the control signal S_1 fails to provide an alternating signature, the switch 144 will remain in its off state. Further, the AC coupling network 952 ensures that the N-
15 channel MOSFET 144 needs a positive voltage between its gate relative to its source to turn on.

(3) Active Current Regulation Circuit

Fig. 10 illustrates a seventh embodiment of the fail-safe-drive system 140 in which an alternative level of fail-safe protection and additional overall efficiency for the fail-safe drive system may be provided. The fail-safe-drive system 140 includes the fail-safe circuit 142 as
20 shown in Fig. 2 in combination with an active-current-regulation circuit 1050. The active-current-regulation circuit 1050 is particularly useful for controlling and regulating the current needed to pull-in and hold-in the first and second solenoid coils 146, 156.

The active-current-regulation circuit 1050 may be a DC-DC converter. In one embodiment, the DC-DC converter may include a step down regulator configured in a standard
25 buck-type configuration. In this standard buck-type configuration, the regulator includes a buck-

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regulator switch 1052, a buck-regulator capacitor 1054, a buck-regulator inductor 1056, a buck-regulator controller 1058, and a buck-regulator rectifier 1060.

The output of the buck regulator, which may be controlled by duty cycles of control signals S_2, may be able to power the fail-safe circuit 142 with various voltages and

5   corresponding current requirements by employing the duty ratio designed into the DC-DC converter. For instance, when operating the fail-safe circuit at a high duty cycle, control signals S_2 may be adjusted to supply enough current to the first common node 172 to actuate the first valve 122. After the first valve 112 is actuated, then the control signals S_2 may be used to adjust the duty ratio of the buck regulator to lower the current supplied to the first common node 172 so

10   as to drive a hold-in current and reduce wasteful heating losses. This active regulation may be used in each of the various modes described above. The following table illustrates the relative regulation the duty ratio of the buck regulator for each of the modes discussed above.

Fail Safe Mode	Duty Cycle of Fail-Safe Circuit 142	Regulator Duty Ratio
Valve Selection	High	Low for Pull-in and then Lower for Hold-in
	Low	High for Pull-in and then Midrange for Hold-in
Operational	Midrange	Midrange for Pull-in and then Lower for Hold-in
OFF	Off	None

TABLE 4

F. Alternative Architecture

15   Figs. 11 and 12 illustrate two exemplary embodiments of fail-safe-drive system 140. These embodiments are particularly useful for low input voltage applications. Like other embodiments, the fail-safe-drive system 140 may control the operation of the first and the second solenoid-controlled valves 112, 122 by facilitating the actuating and/or de-actuating of the first and second solenoid-controlled valves 112, 122. Independent actuation and/or de-actuation of

the valves 112, 122 may be brought about by operating the fail-safe-drive system 140 at different duty cycles.

With reference to Fig. 11, high-side and low-side supply conductors 164, 166 collectively couple the input power supply 162 to the high side drive circuit 850 and the fail-safe circuit 142.

5   While other power regulation may be deployed, the input power supply 162 may also be embodied as a thermopile. In general, a thermopile may contain a series of thermoelements. Each thermoelement can be constructed from a thin wire made of two materials of different thermal activity. When a temperature difference occurs between the two ends of a wire, an electrical tension ("thermotension") develops. Connecting several thermoelements in series adds

10   together the thermotension of each element, producing a useful electrical output signal.

Using a thermopile is particularly advantageous in systems that do not employ external power. In systems such as water heaters, the thermopile can be maintained in a pilot light or other flame so as to develop the input electrical signal. For example, the input electrical signal supplied by the thermopile can develop a voltage of about 0.4 to 0.8 volts. This voltage may be

15   particularly useful for driving first and second solenoid coils 146, 156 designed for actuation at low voltages and currents.

In the alternative embodiment shown in Fig. 11, the energy-transfer device 150 of the fail-safe circuit 142 may be configured as shown with a first capacitor 1110 coupled in parallel with the first solenoid coil 146; a second switch 1112 for coupling the input electrical signal to

20   the second solenoid coil 156, and a rectifier 1114, a second capacitor 1116, a resistor 1118 network for controlling the on and off states of the second switch 1112 and in turn current flow through the second solenoid coil 156. The architecture of these elements may be the same as any similar element noted above. For instance, the first and second capacitors 1110, 1116 may be polarized or non-polarized; the rectifier 1114 may be a diode; the second switch 1112 may be a

25   transistor; etc. While not mentioned above, those skilled in the art will recognize resistor 1118 may be a carbon-based, silicon-based or any other type resistor.

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While the second switch 1112 may take one of many forms, for convenience, the second switch 1112 in Fig. 11 is illustrated as a PNP bipolar transistor. The base of the transistor is coupled in series with the resistor 1118. Depending on the duty cycle, the energy-transfer device 150, through the rectifier 1114, second capacitor 1116, and resistor 1118 network, supplies a

5   control signal to bias the base for the second transistor 1112. When the base is biased low, the second transistor 1112 turns on, causing the current I_2 to flow in the second solenoid coil 156. If current I_2 rises above the pull-in threshold, then the second valve 122 may actuate.

The operation of the fail-safe circuit 142 for the present embodiments at the high, mid-range and low duty cycles may be as follows. The operation is described in reference to Fig. 11,

10   but as shown in the alternative embodiment of Fig. 12, a P-channel MOSFET may be used instead of a PNP transistor. As such, the fail-safe circuit 142 may include a second resistor 1220 that provides a discharge path for the second capacitor 1116, and a combination of rectifier 1222 and zener diode 1224 that provide voltage limiting for the second capacitor 1116.

(1) High Duty Cycle

15   When switch 144 is in the on state, the voltage between the first common node 172 and the common low-side- node 174 becomes approximately V_{in}. From this voltage, the current I_1 flows through the first solenoid coil 146 as the first capacitor 1110 charges. Given the long duration of the on-state of the switch 144, the first capacitor 1110 charges to V_{in} and current I_1 flowing through the first solenoid coil 146 rises above the pull-in threshold causing the first

20   valve 112 to actuate.

While the input electrical signal may be sufficient to supply current above the pull-in and hold-in thresholds, the first capacitor 1110 aids in actuating the first valve 112 and de-actuating the second valve 122 in the off state. The addition of the first capacitor 1110 increases the range of duty cycles at which only the first valve 112 actuates.

25   In the orientation shown, the rectifier 1114 is in a reverse biased orientation, and thus, it is not conducting. This in turn prevents the second capacitor 1116 from charging. With the

second common node 176 at approximately zero potential, no current flows through the resistor 1118, which sends the second switch 1112 a control signal to turn off. Consequently, little or no current I_2 flows through the second solenoid coil 156. With little or no second current flowing through the second solenoid coil 156, the second valve 122 remains or operates in a de-actuated

5   state.

When switch 144 is turned off for the remainder of the switching cycle, the charge on the first capacitor 1110 supplies the first current to first solenoid coil 146. In some instances, this charge may deplete or become slightly reversely charged by the freewheeling current I_1. Since there is little or no freewheeling through the second capacitor 1116 (the first capacitor 1110

10   provides the freewheeling path), the second capacitor 1116 stays uncharged and the second switch 1112 stays in off state. And, in turn, the second valve 122 stays unactuated.

The resistor 1118 may be used to regulate bias current of the second switch 1112. The resistor 1118 also provides additional fail-safe attributes. If for example, the second switch 1112 is shorted (e.g., the emitter, base, and collector are shorted together), the resistor 1118 may limit

15   the current that can flow through the second switch 1112, the resistor 1118, the rectifier 1116, and the first solenoid coil 146. This makes de-actuating the first valve 112 possible by turning off the first switch 144.

(2) Low Duty Cycle

During the on state of the switch 144, the current I_1 builds in the first solenoid coil 146.

20   But because the duration of the on state duration is short, the average of current I_1 fails to meet or exceed the pull-in threshold. The first capacitor 1110, however, charges to a voltage approximately equal to V_{in}. Given its reverse bias orientation, the rectifier 1116 does not conduct.

During the OFF state time, the current I_i freewheels through rectifier 1114, and a negative

25   potential develops in the second capacitor 1116. Thus, the second common node 176, i.e., the intersection of the rectifier 1114 and the resistor 1118 is at the same negative potential. This

negative potential in combination with the input electrical signal provides a bias to the base of the second switch 1112 causing the input power supply 162 to supply the input electrical signal so as to cause the current I_2 to flow through the second solenoid coil 156. Since the long duration of the off state, the average of current I_2 builds to a value that meets or exceeds the pull-in current, actuating the second valve 122.

At beginning of the off state, the first capacitor 1110 supplies the current I_1 for a short portion of the off state as it discharges. After the first capacitor 1110 is discharged, the current I_1 freewheels through the second capacitor 1116 and the rectifier 1114. As it freewheels, the current I_1 charges the second capacitor 1116 to a negative potential. As noted, the first capacitor 1110 may have less storage capacity than the second capacitor 1116.

Consequently, a small portion of the freewheeling current I_1 flows through the first capacitor 1110, reversely charging it. The current I_1 decreases to zero before the on state starts and average of the current I_1 not sufficient to activate first valve 112. Although the current I_1 not sufficient to activate the first valve 112, it may still be greater than the base current necessary to bias the second switch 1112, maintaining the negative potential at the second common node 176. With the base biased on, the current I_2 meets or exceeds the pull-in and/or hold-in thresholds for the solenoid coil 156 causing the second valve 122 to be maintained in the actuated state.

(3) Mid-range Duty Cycle

During the on state of the switch 144, the current I_1 flowing through the first solenoid coil 146 increases, and the first capacitor 1110 charges to a value approximately equal to the input voltage. At beginning of the off state, the first capacitor 1110 supplies current I_1 for a portion of the off state as it discharges. Once discharged, the current I_1 built up in the first solenoid coil 146 freewheels through the second capacitor 1116 and the rectifier 1114. This in turn charges the second capacitor 1116 to a negative potential.

As noted, the first capacitor 1110 may be have less storage capacity that the second capacitor 1114. Consequently, a small portion of the freewheeling current I_1 flows through the

first capacitor 1110, reversely charging it. But unlike the low duty cycle, the current I_1 does not decrease to zero before the on state starts. The current I_1 (and the average thereof) is sufficient to actuate the first valve 112. The negative potential on the capacitor 1116 keeps the base of the second switch 1112 biased, which in turn causes the current I_2 to meet or exceed the pull-in

5   and/or hold-in thresholds.

The second capacitor 1116 is charged by the current I_1 and discharged by the base current of the second switch 1112. The second capacitor 1116 can maintain the negative potential at the second common node 176 during both the on and off state of switch 144 even though the charging time is shorter than the discharging time. This may happen because the current I_1 is

10   much higher than the base current of the second switch 1112.

(4) Very Low Duty Cycle

During the on state of the switch 144 at a very low duty cycle, e.g., a duty cycle less than about 10%, the current I_1 cannot rise above the pull-in threshold. During off state, any potential in the first capacitor 1110 cannot source enough current I_1 to actuate the first solenoid coil 146.

15   A small amount of current I_1 may freewheel through 1110, and not the second capacitor 1116. Little or no negative potential is established at the second common node 176. Thus, during this duty cycle, both the first and second valves 112, 122 are de-actuated.

G. Conclusion

In view of the wide variety of embodiments to which the principles of the present

20   invention can be applied, it should be understood that the illustrated embodiments are exemplary only, and should not be taken as limiting the scope of the present invention. For example, the steps of the operational modes may be taken in sequences other than those described, and more or fewer elements may be used in the block diagrams. In addition, use of the term "means" in any claim is intended to invoke 35 U.S.C. §112, paragraph 6, and any claim without the word

25   "means" is not so intended. Therefore, all embodiments that come within the scope and spirit of the following claims and equivalents thereto are claimed as the invention.

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It will be understood, however, that changes and modifications may be made to the invention without deviating from its true spirit and scope, as defined by the following claims.